Animated gifs on some slides.
See ppt version or separate indico attachment.

Probing for anomalous HVV couplings in production and decay $H \to 4\ell$ at CMS

Heshy Roskes (Johns Hopkins University)

for the CMS collaboration

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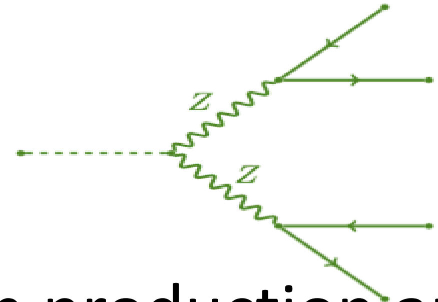
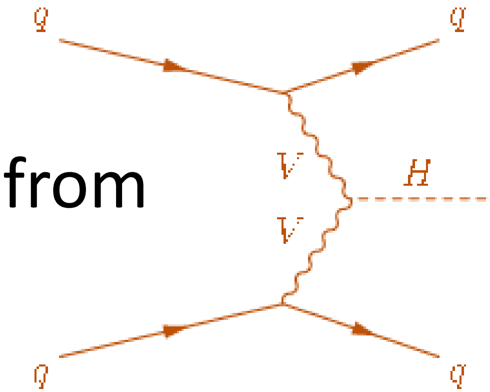
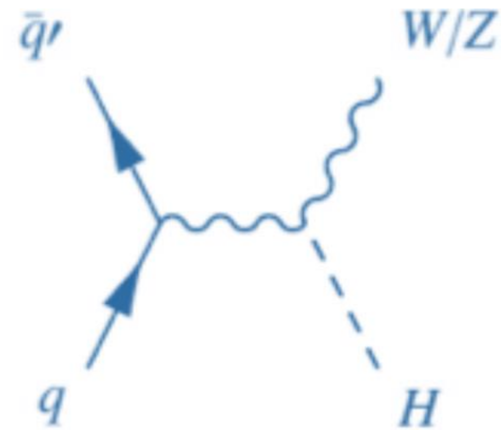
Anomalous couplings



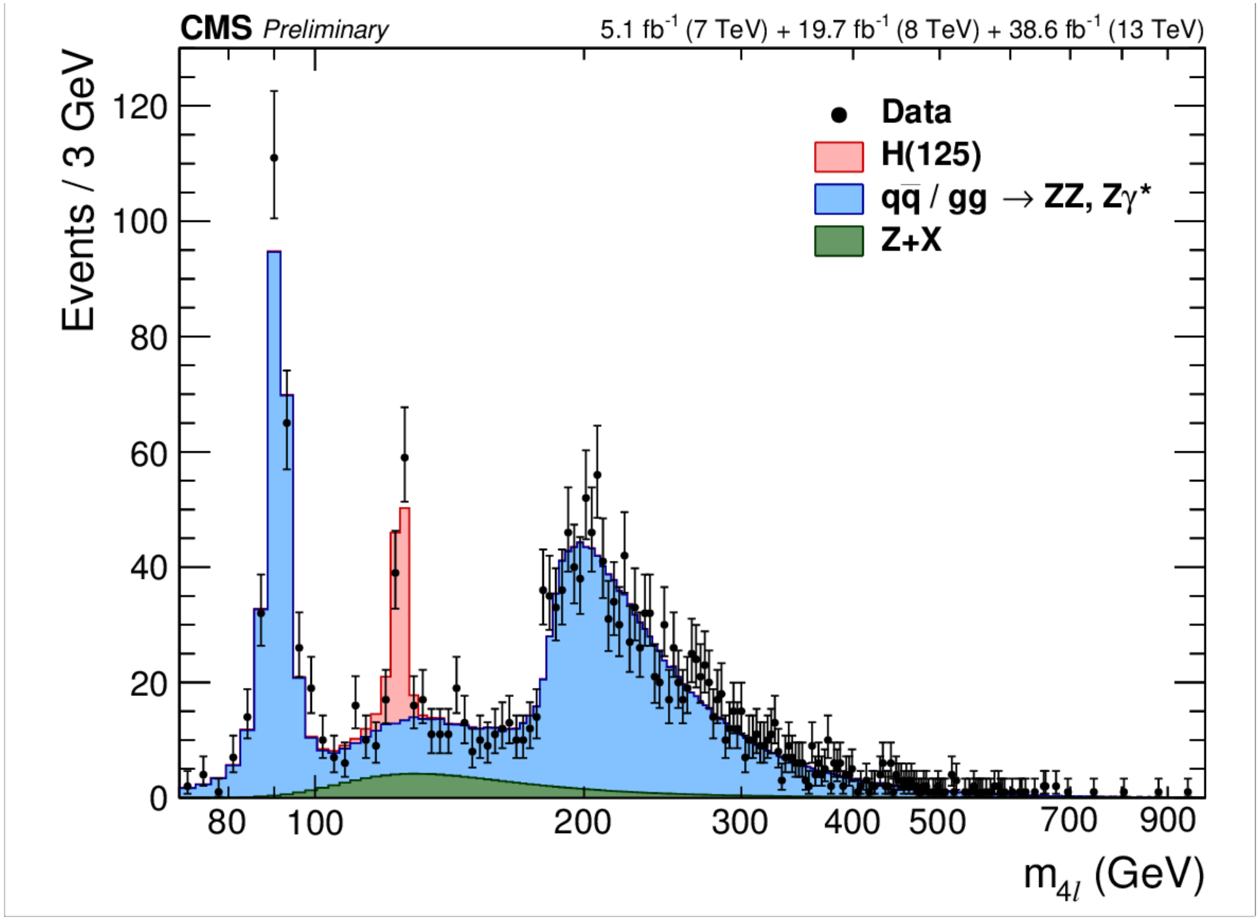
- Search for anomalous HVV couplings in production and decay in the $H \to 4l$ channel
- Kinematics of decay
- New: kinematics of jets from VBF and VH production





- Use matrix element (MELA) discriminants
  - optimally select VBF and VH events
  - optimally separate different contributions to the amplitude
- Combine with Run 1 CMS analysis

$H(125) \to 4\ell$



References:

Run 1:

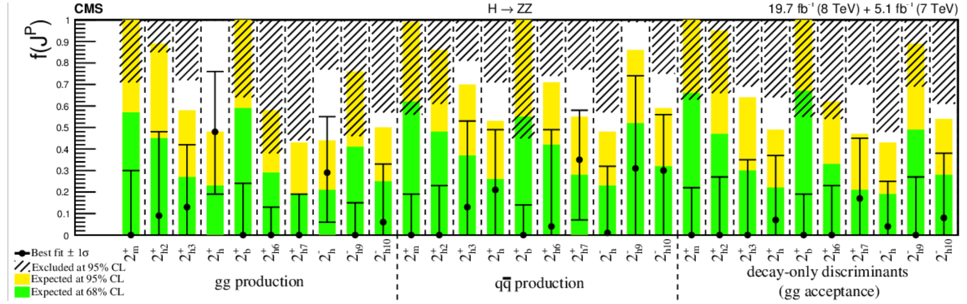
- [CMS-HIG-14-018](CMS-HIG-14-018)
  spin
  anomalous couplings

Run 2:

- [CMS-PAS-HIG-16-041](CMS-PAS-HIG-16-041)
  properties
- [CMS-PAS-HIG-17-011](CMS-PAS-HIG-17-011)
  anomalous couplings

- What is it?
- How does it interact with other particles?

CMS&ATLAS results



- Run 1: exclude spin 1 and 2
- Set limits on spin 0 anomalous couplings

CMS

- Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs CMS-HIG-12-041, arXiv:1212.6639
- Measurement of the properties of a Higgs boson in the four-lepton final state arXiv:1312.5353, CMS-HIG-13-002
- Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV arXiv:1411.3441, CMS-HIG-14-018
- Limits on the Higgs boson lifetime and width from its decay to four charged leptons arXiv:1507.06656, CMS-HIG-14-036

$f_{\Lambda Q}$

- Combined search for anomalous pseudoscalar HVV couplings in VH production and H to VV decay arXiv:1602.04305, CMS-HIG-14-035

ATLAS

- Evidence for the spin-0 nature of the Higgs boson using ATLAS data ATLAS arXiv:1307.1432
- Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector ATLAS arXiv:1506.05669
- Test of CP Invariance in vector-boson fusion production of the Higgs boson using the Optimal Observable method in the ditau decay channel with the ATLAS detector ATLAS arXiv:1602.04516

VV Production (decay to $f\bar{f}$)

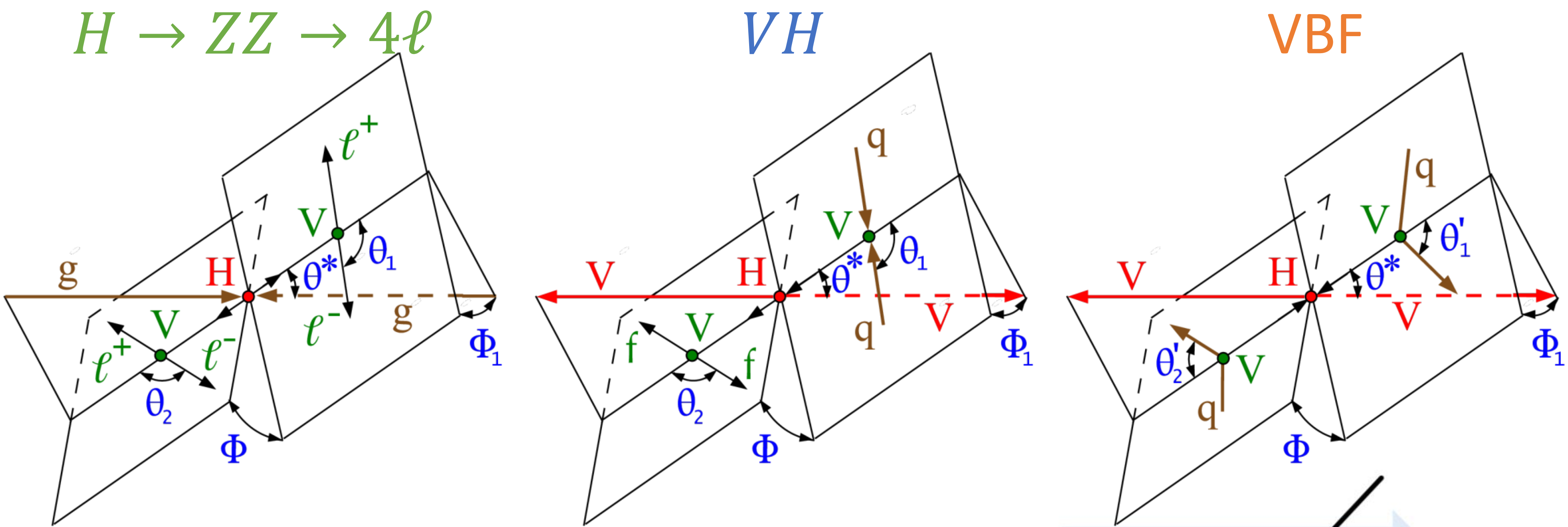
- Measurements of properties of the Higgs boson and search for an additional resonance in the four-lepton final state at √s = 13 TeV, CMS-PAS-HIG-16-033
- Constraints on anomalous Higgs boson couplings in production and decay H→4ℓ, CMS-PAS-HIG-17-011

This analysis

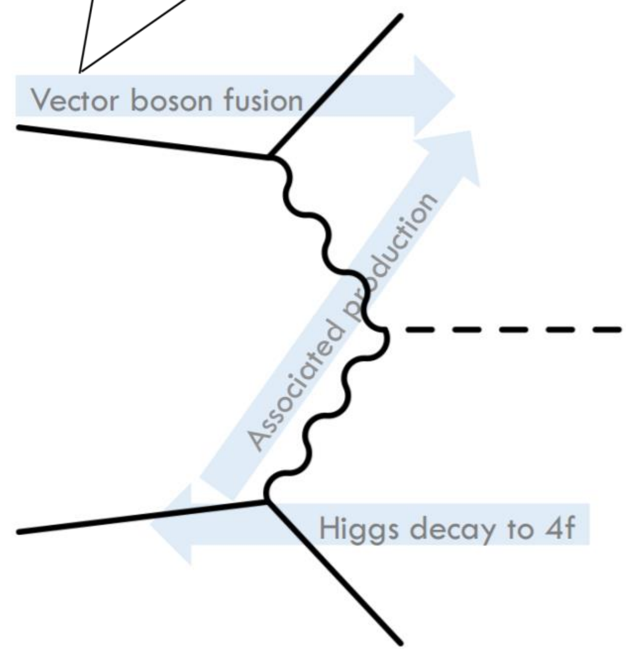
- Measurement of inclusive and differential cross sections in the H → ZZ∗ → 4l decay channel at 13 TeV with the ATLAS detector ATLAS-CONF-2017-032

Run 2 results

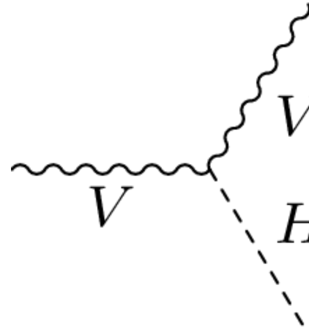
Kinematics

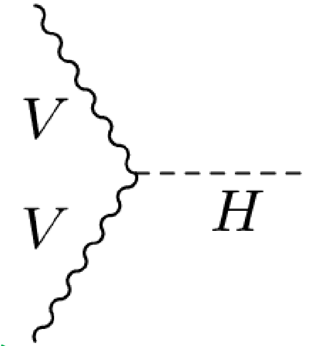


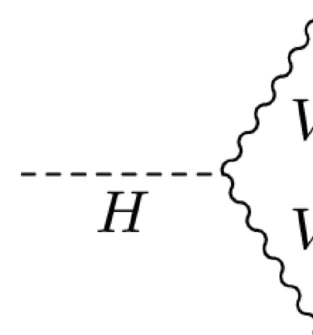
- For a given $m_{4\ell}$, four-fermion system in production or decay is defined by:
  - 5 angles
  - Two $q^2_{V_i}$ of difermion systems
- For the production+decay: two HVV vertices
- 13 independent observables remain



HVV amplitude

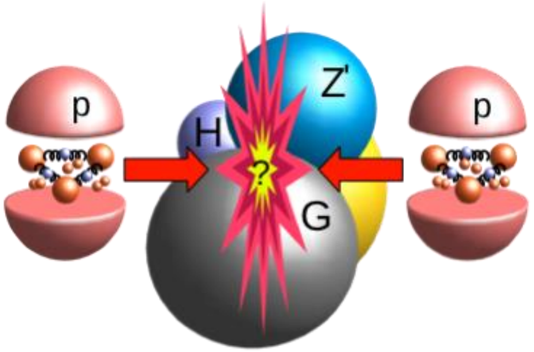






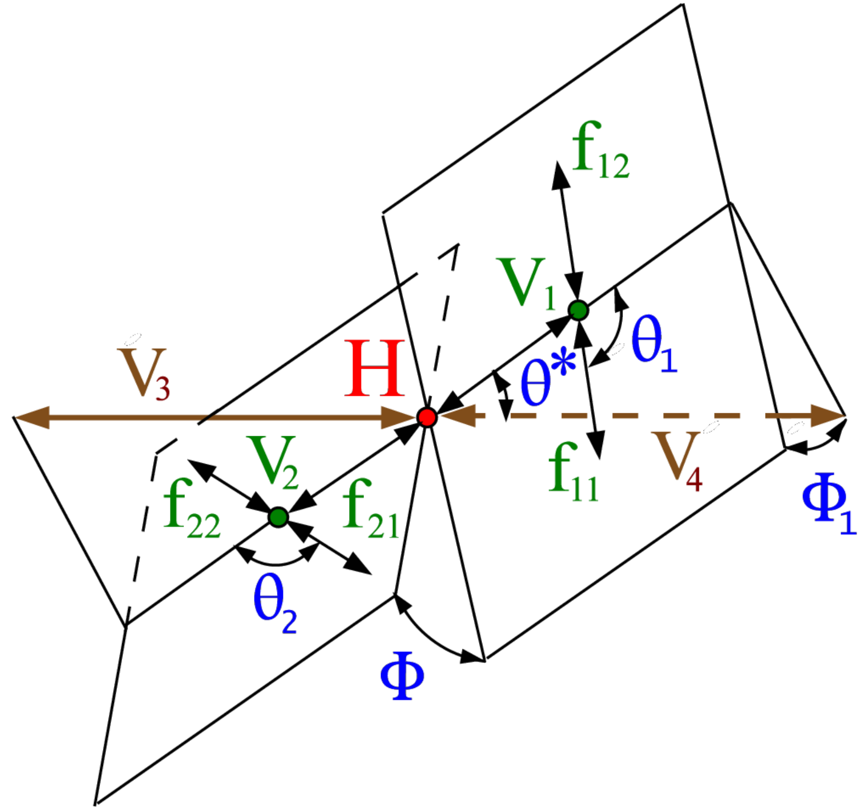
- $A(HVV) \sim \left[a_1^{VV} + \frac{q_{V_1}^2 + q_{V_2}^2}{\left(\Lambda_1^{VV}\right)^2} \right] m_{V_1}^2 \epsilon_{V_1}^* \epsilon_{V_2}^* +$
  $a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$
- $VV = ZZ, WW, Z\gamma, \gamma\gamma$
- SM, tree level: $a_1^{ZZ} = a_1^{WW} = 2$, others $= 0$
- Assume $a_i^{ZZ} = a_i^{WW}$, call it "a_i"
- Assume no q^2 cutoff for anomalous couplings
- Measure $a_2, a_3, \Lambda_1, \Lambda_1^{Z\gamma}$
  - $a_{2,3}^{Z\gamma,\gamma\gamma}$ are already constrained from onshell photons
- Parameterize as fractional cross section $f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j}$
  and relative phase $\phi_{ai} = \arg\left(\frac{a_i}{a_1}\right)$

Tools



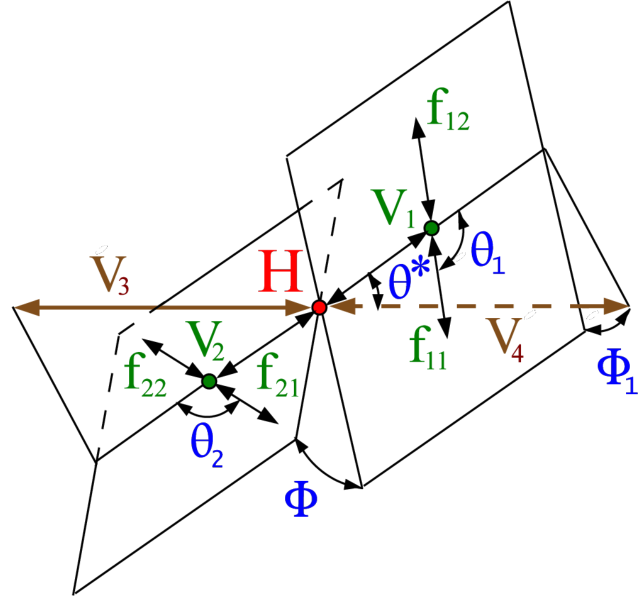
- JHUGen
  - Generate samples with arbitrary couplings
    - $gg/q\bar{q} \rightarrow X \rightarrow ZZ/WW \rightarrow 4f$ for X spin 0, 1, 2
    - VBF, VH, ggH with 0, 1, or 2 QCD jets, ttH, bbH, tqH
- MELA—Matrix Element Likelihood Approach
  - Matrix element calculations
    - JHUGen for signal
    - MCFM for background
  - Calculate discriminants to distinguish hypotheses
  - Reweight generated samples to different hypotheses

Contributions



- Background
  - $q\bar{q}/gg \to ZZ$
  - $Z + X$
- Signal
  - ggH, VBF, VH, ttH
    - HVV couplings in decay
    - HVV couplings in production and decay
  - SM, anomalous, and interference contributions
- Want to isolate each component to constrain couplings
- 7 or 13 kinematic observables ($+m_{4\ell}$ for bkg separation)
  - too many to use them all

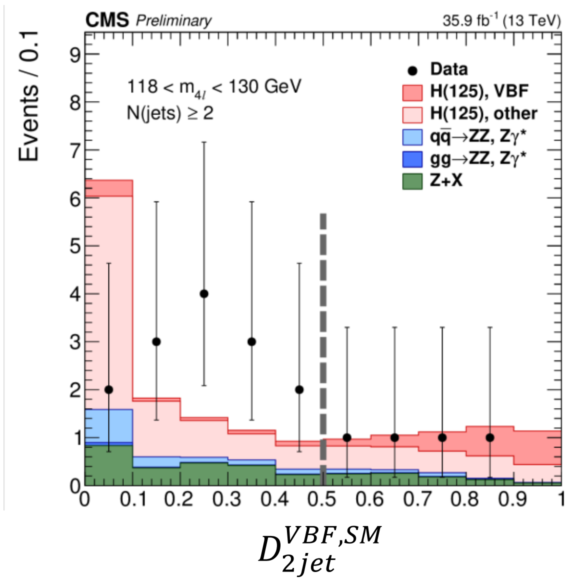
Discriminants

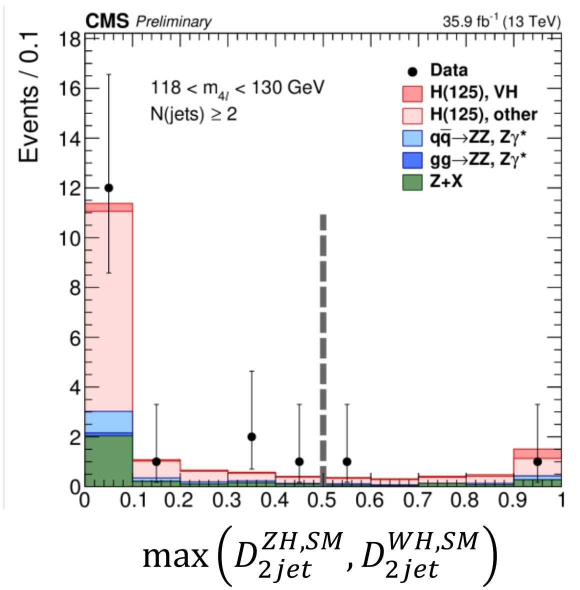


- Two basic types of discriminants:
  - $D_{alt} = \frac{p_{sig}}{p_{sig}+p_{alt}}$
    - **Optimal** to distinguish pure SM signal from alternate hypothesis
    - Alternate hypothesis could be background, another coupling model, or another signal production mode
  - $D_{int} = \frac{p_{int}}{p_{sig}+p_{alt}}$
    - Together with D_{alt}, **optimal** to also isolate the interference contribution
- p_{sig}, p_{alt}, p_{int} are calculated through MELA using matrix element probabilities

Discriminants 1

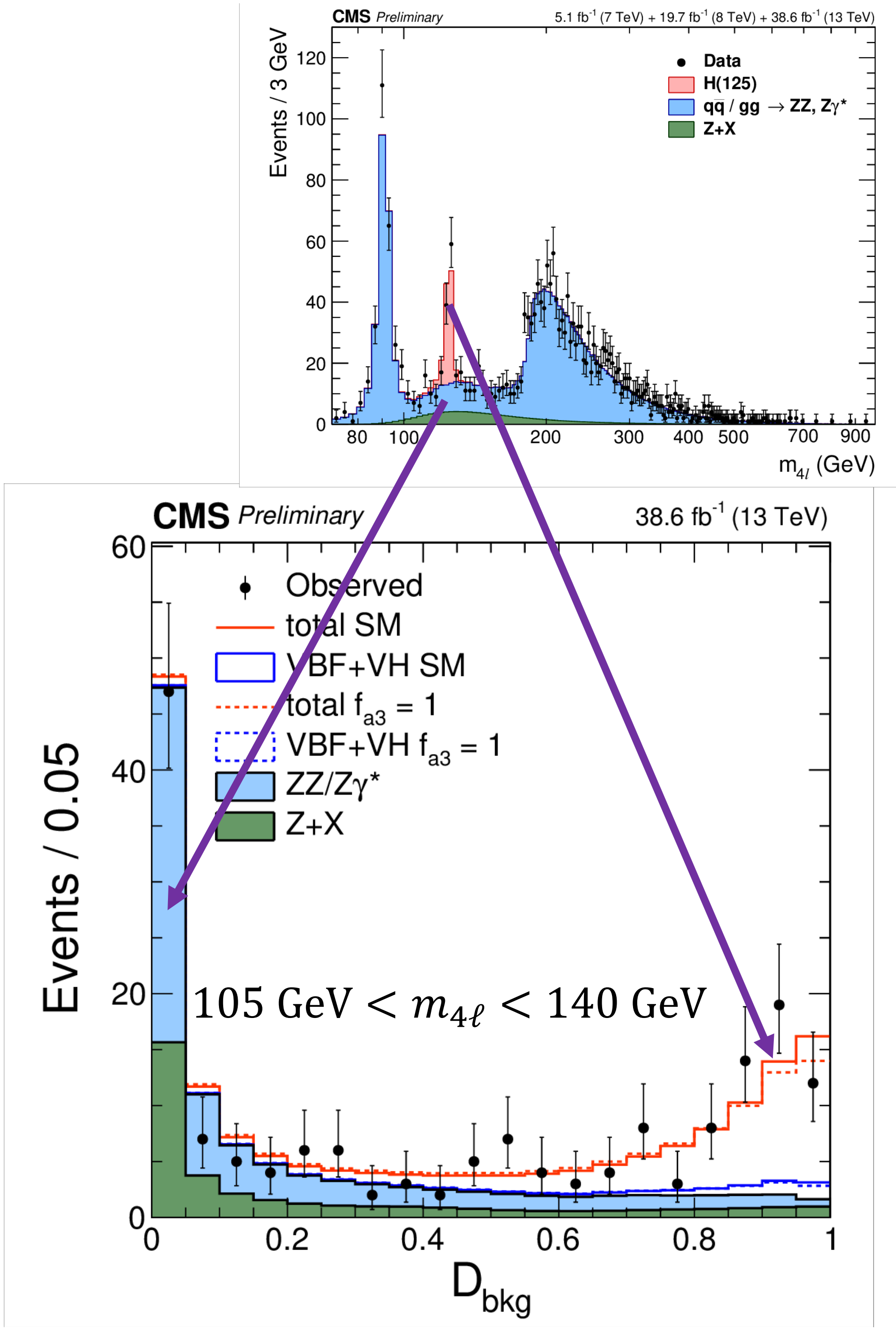
- $D_{2jet}^{VBF/ZH/WH} = \frac{p_{VBF/ZH/WH}}{p_{VBF/ZH/WH}+p_{Hjj}}$
- Separate associated production from QCD jets
- VBF-jet category:
    - $D_{2jet}^{VBF,SM} > 0.5$ or $D_{2jet}^{VBF,BSM} > 0.5$
- VH-jet category:
    - $D_{2jet}^{ZH,SM} > 0.5$ or $D_{2jet}^{ZH,BSM} > 0.5$ or $D_{2jet}^{WH,SM} > 0.5$ or $D_{2jet}^{WH,BSM} > 0.5$
- Untagged category:
    - Everything else
- Use D_{2jet}^{SM} and D_{2jet}^{BSM} to get optimal separation for both extreme hypotheses





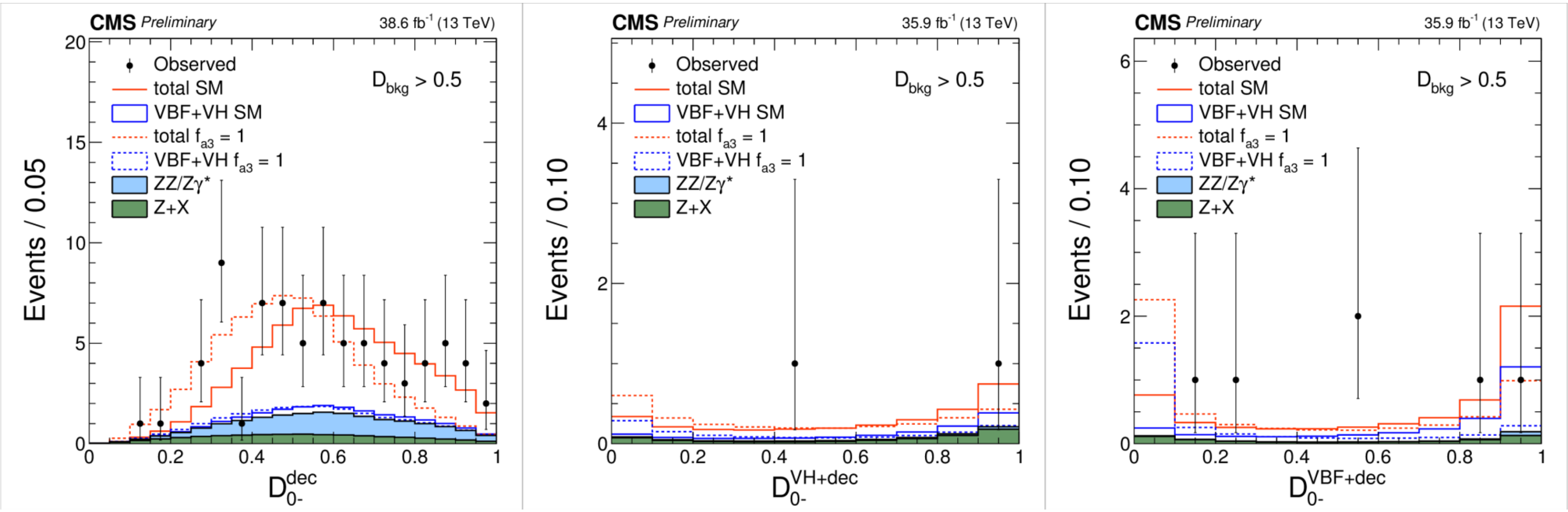
Discriminants 2

- Use 3D templates to parameterize the signal and background for each category
- $\boldsymbol{D_{bkg}}$, D_{ai}, D_{int}
- $D_{bkg} = \frac{p_{sig}}{p_{sig}+p_{bkg}}$
  - Used for all 3 categories
  - $m_{4\ell}$ + decay kinematics



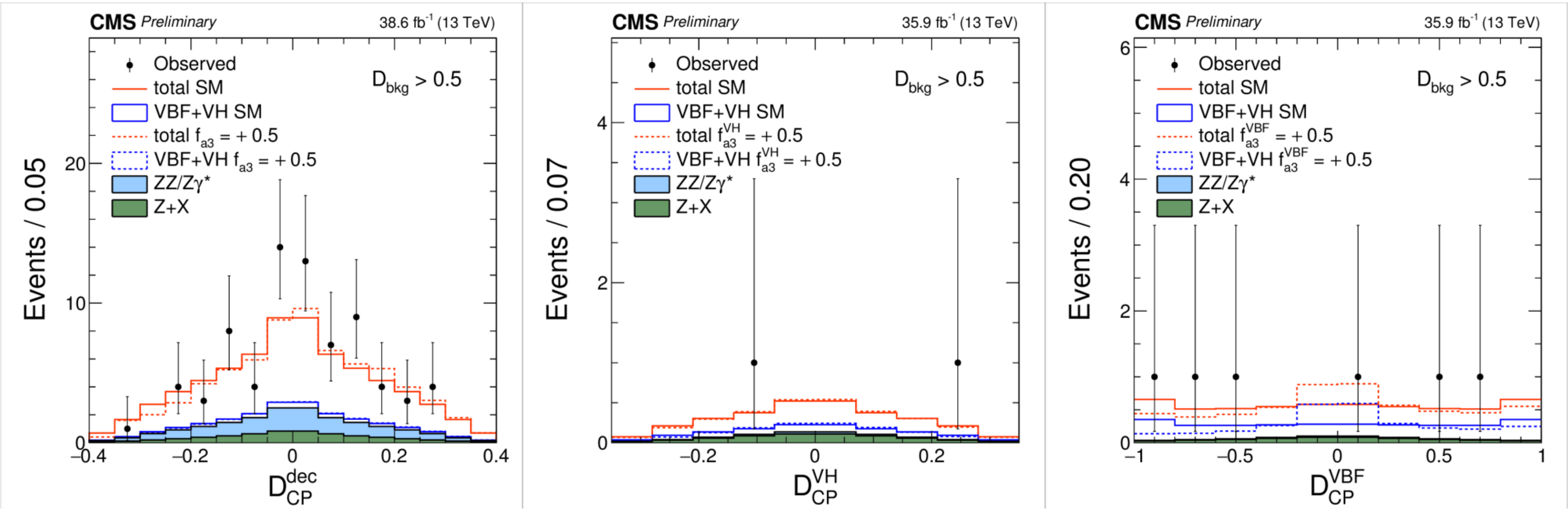
Discriminants 3

- D_{bkg}, $\boldsymbol{D_{ai}}$, D_{int}
- $D_{ai} = \frac{p_{sig}}{p_{sig}+p_{ai}}$
- Tagged categories: use production×decay probabilities
- Untagged: use decay probabilities only
- Example: D_{0-} for the f_{a3} analysis



Discriminants 4

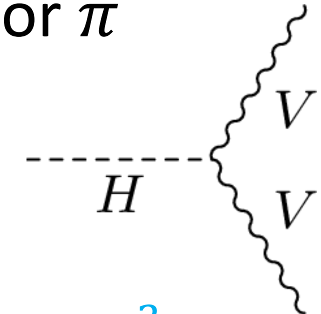
- D_{bkg}, D_{ai}, $\boldsymbol{D_{int}}$
- $D_{int} = \dfrac{p_{int}}{p_{sig}+p_{alt}}$
- Tagged categories: use production probabilities
- Untagged: use decay probabilities



$$f_{ai} = \frac{|a_i|^2 \sigma_i}{|a_1|^2 \sigma_1 + |a_i|^2 \sigma_i + \cdots}$$

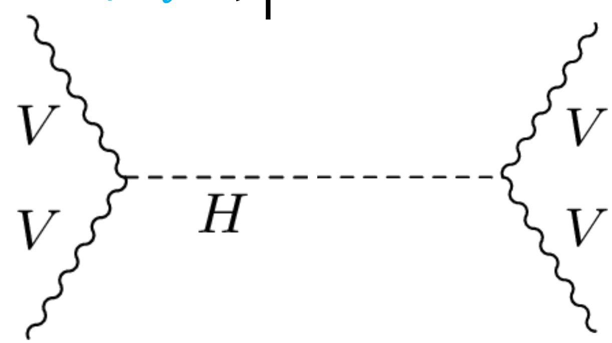
Likelihood fit

- Assume real couplings, $\phi_{ai} = 0$ or π
- ggH, only one HVV vertex:
  - $p(f_{ai}, \vec{\Omega})$
    $\sim |a_1 A_1 + a_i A_i|^2$
    $\sim T_0(\vec{\Omega}) + \left|\frac{a_i}{a_1}\right| \cos\phi_{ai}\, T_1(\vec{\Omega}) + \left|\frac{a_i}{a_1}\right|^2 T_2(\vec{\Omega})$

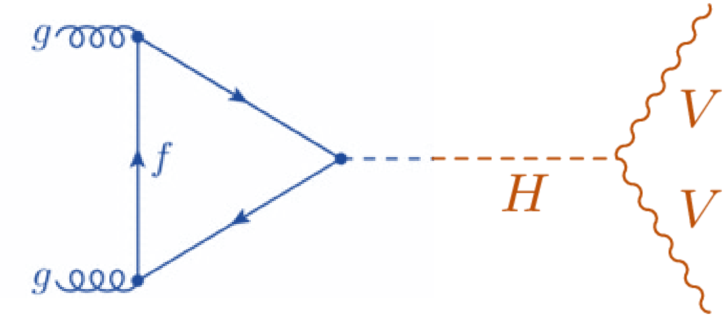


$$\left|\frac{a_i}{a_1}\right| = \sqrt{\frac{f_{ai}}{f_{a1}} \frac{\sigma_1}{\sigma_i}}$$

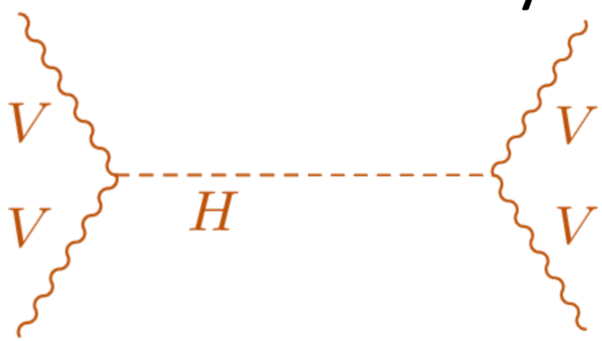
- VBF or VH, two HVV vertices
  - $p(f_{ai}, \vec{\Omega})$
    $\sim \left|(a_1 A_1^{prod} + a_i A_i^{prod})(a_1 A_1^{dec} + a_i A_i^{dec})\right|^2$
    $\sim \sum_{j=0}^{4} \left|\frac{a_i}{a_1}\right|^j \cos^j \phi_{ai}\, T_j(\vec{\Omega})$

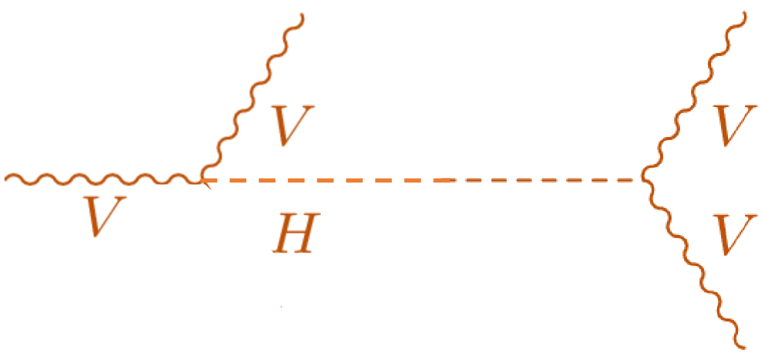


Signal strength



- Want to decouple ratios of couplings f_{ai} from the signal strengths μ_i
- Allow signal strength for production via fermion couplings μ_f and boson couplings μ_V to float independently
- Constrained by category distribution of events





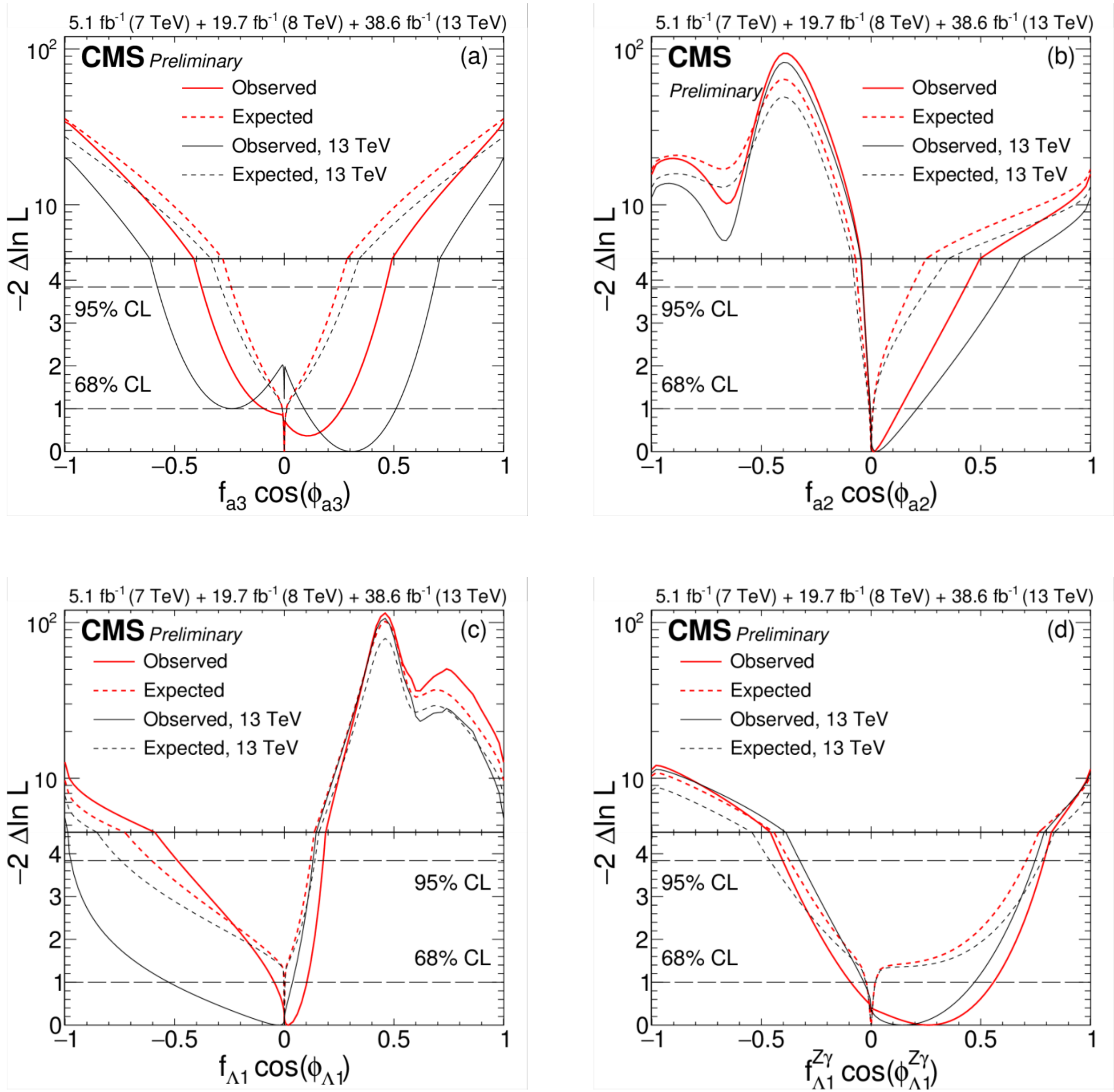
Event distribution

- First number is for SM, (second) is for $f_{a3} = 1$
- Use categorization for f_{a3} analysis, others are a bit different
  - (In particular, fewer observed events in VBF-jets)

	VBF-jets	VH-jets	untagged	2015
VBF signal	2.4 (1.6)	0.1 (0.1)	2.2 (0.3)	0.4 (0.2)
ZH signal	0.1 (0.2)	0.3 (0.5)	0.7 (1.0)	0.1 (0.1)
WH signal	0.1 (0.3)	0.3 (1.0)	0.8 (2.2)	0.1 (0.3)
$gg \rightarrow H$ signal	3.2 (3.3)	1.9 (2.0)	49.6 (49.4)	4.4 (4.4)
$t\bar{t}H$ signal	0.1 (0.1)	0.0 (0.0)	0.5 (0.6)	0.0 (0.1)
$q\bar{q} \rightarrow 4\ell$ bkg	0.9	1.1	56.3	5.2
$gg \rightarrow 4\ell$ bkg	0.1	0.1	5.5	0.5
VBF/VVV bkg	0.1	0.0	0.4	0.0
Z+X bkg	3.6	2.0	29.1	1.7
Total expected	10.7	5.8	145.2	12.9
Total observed	11	2	145	11

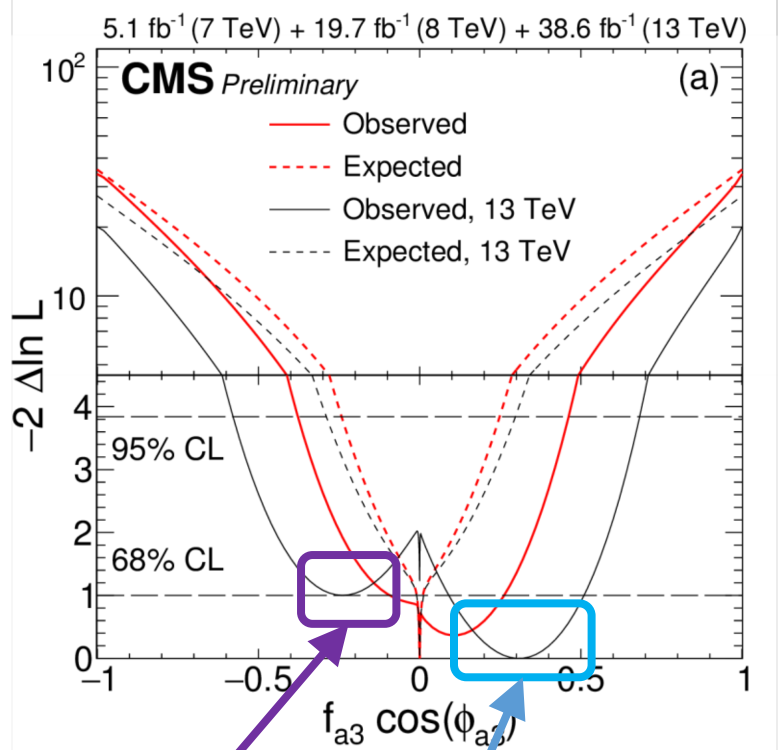
Results

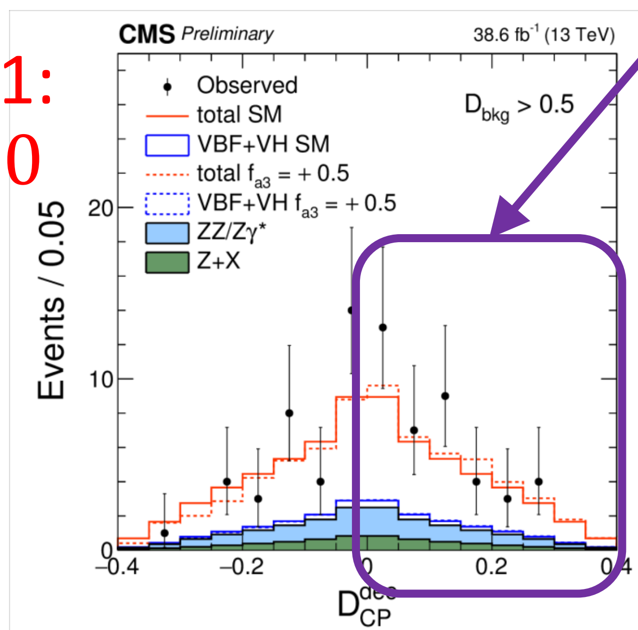
- Scans for each parameter
- 13 TeV only, and combination with Run 1 result

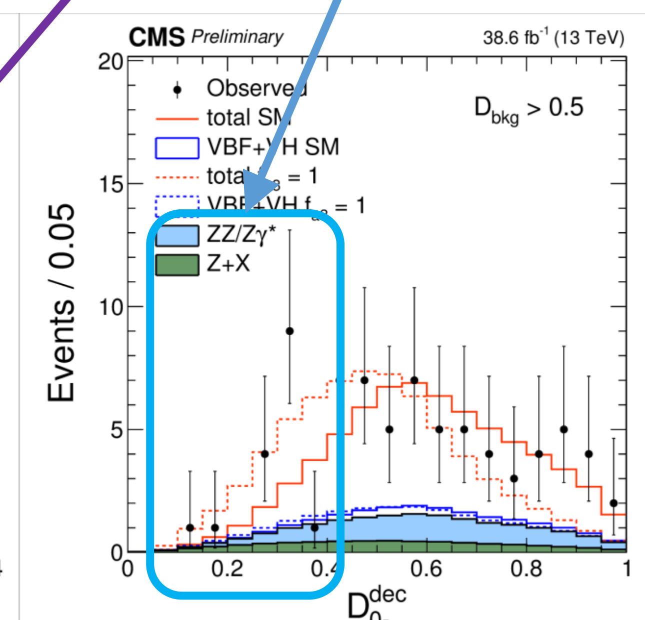


More details: f_{a3}

- 1D projections help to explain
- Small excess of events at smaller values of D_{0-}^{dec}
  - Minimum away from 0
- D_{CP} has small excess on the right
  - +0.3 is favored over -0.3
- Combine with Run 1: minimum at $f_{a3} = 0$

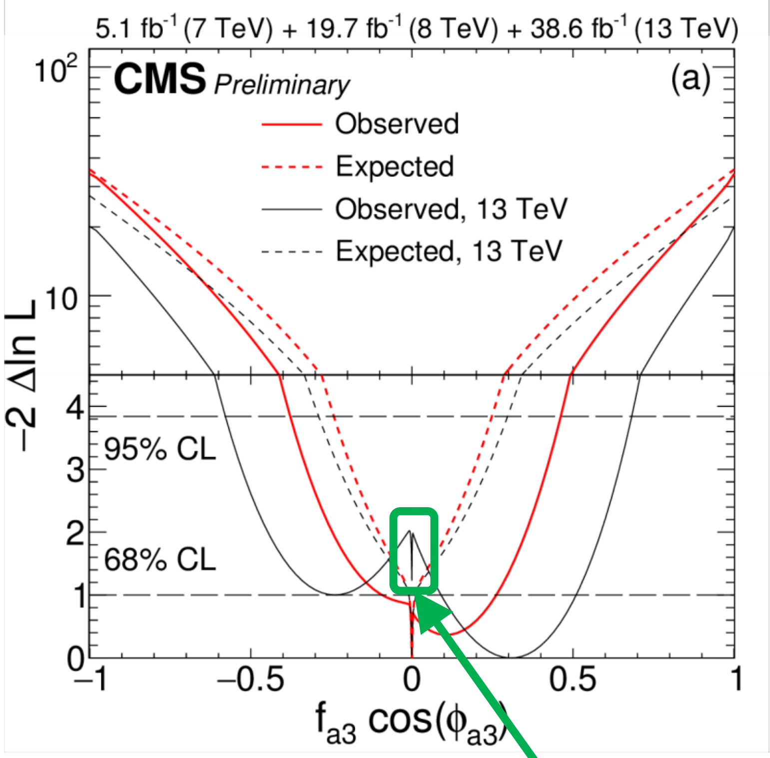


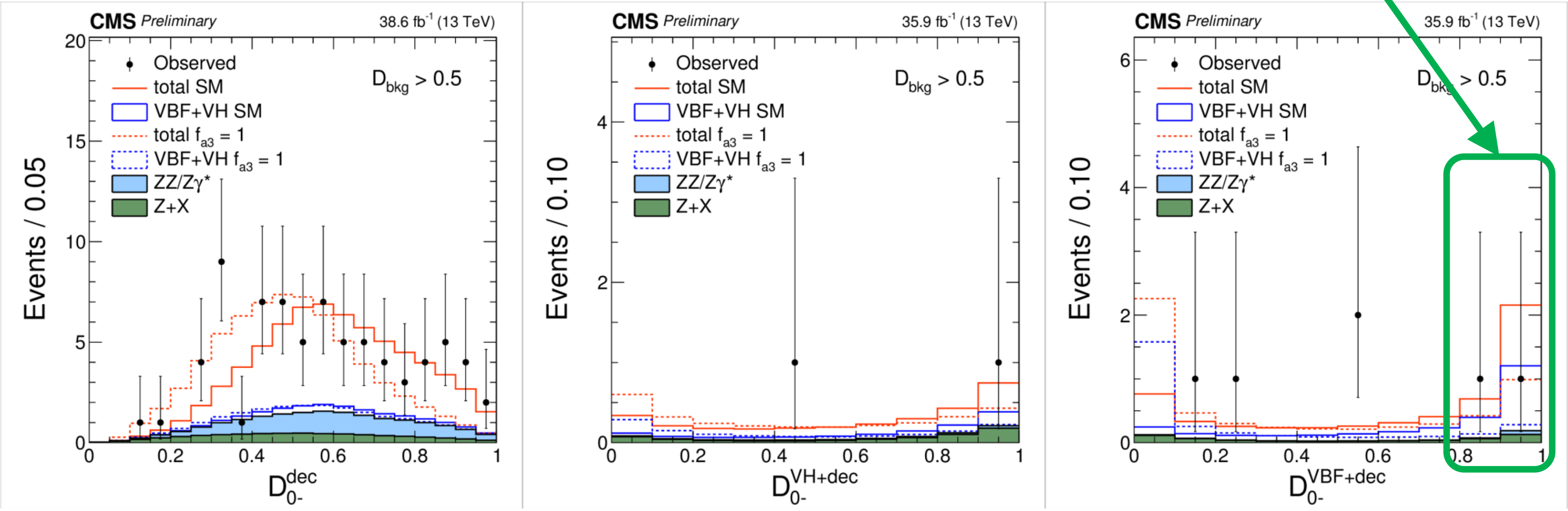




More details: f_{a3}

- VBF and VH are sensitive to very small f_{a3}
- Once $f_{a3} \gtrsim 0.01$, more favorable to set $\mu_V \to 0$

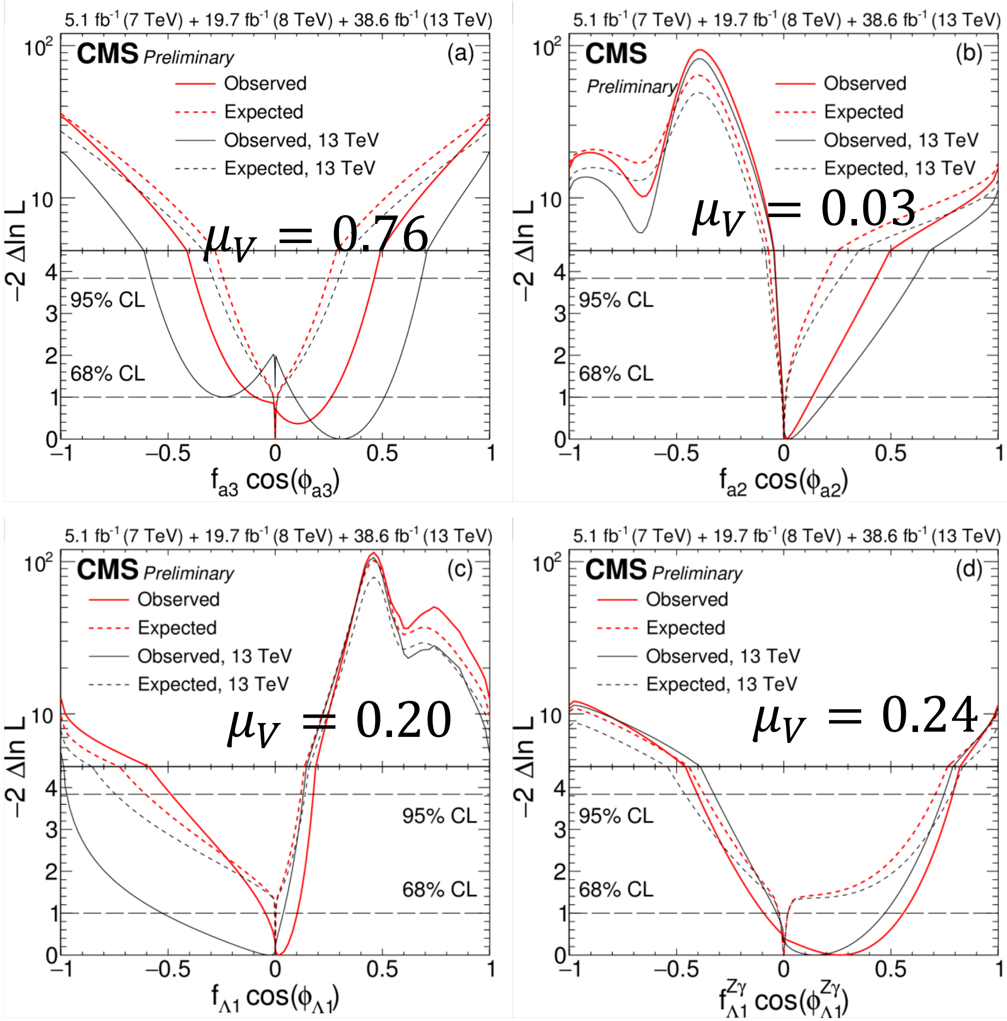




μ_V

- Observe fewer VBF and VH events than expected
- Best fit μ_V for $f_{ai} = 0$ is < 1 (values on plots)

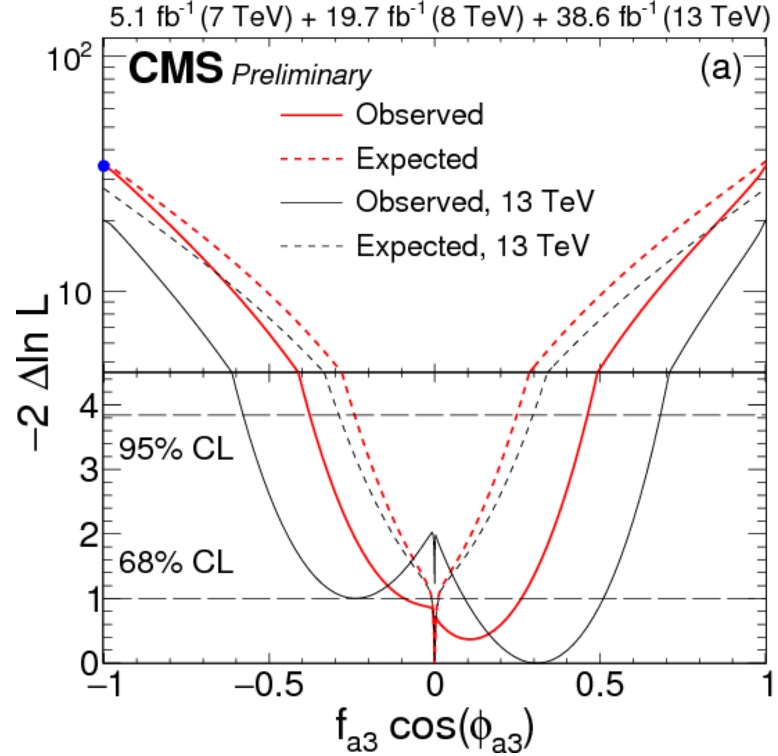
➢ Narrow minima not as deep as expected

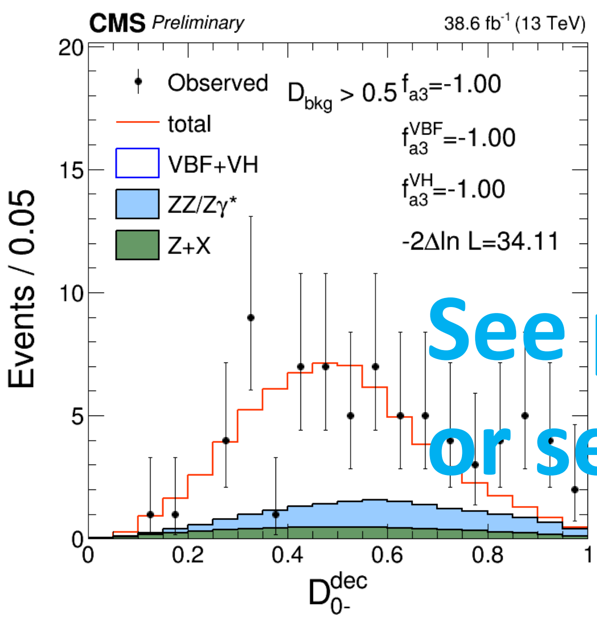


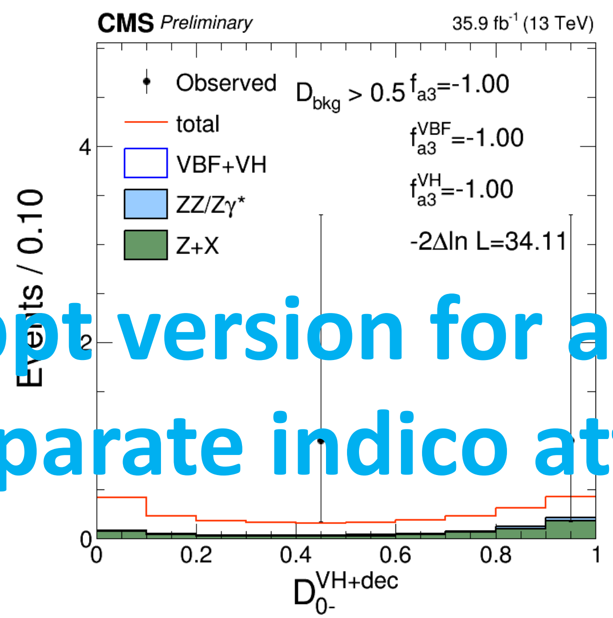
Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$
$f_{a2}\cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.02^{+0.08}_{-0.06}$ $[-0.49, 0.18]$	$0.000^{+0.003}_{-0.002}$ $[-0.60, 0.12]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.26^{+0.30}_{-0.35}$ $[-0.40, 0.79]$	$0.000^{+0.019}_{-0.022}$ $[-0.37, 0.71]$

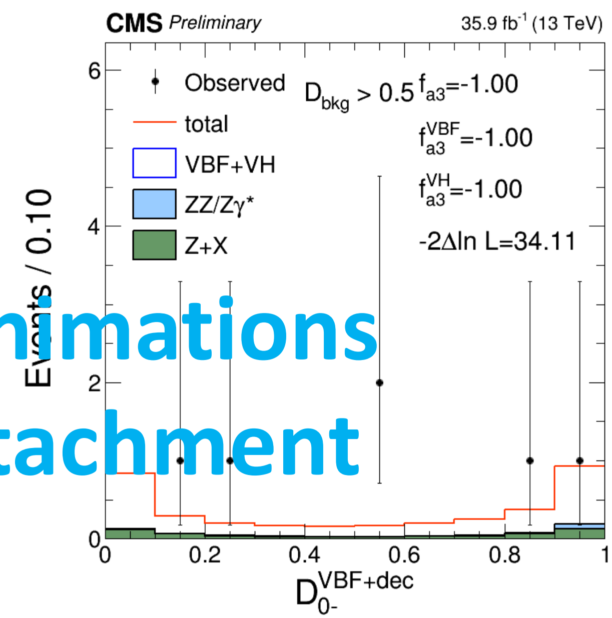
More details: f_{a3}

- Animations: each frame uses the best fit μ_V and μ_f
- $f_{a3}^{VBF/VH}$ are the cross section fractions for those processes
- Watch what happens when $f_{a3} \lesssim 0.01$



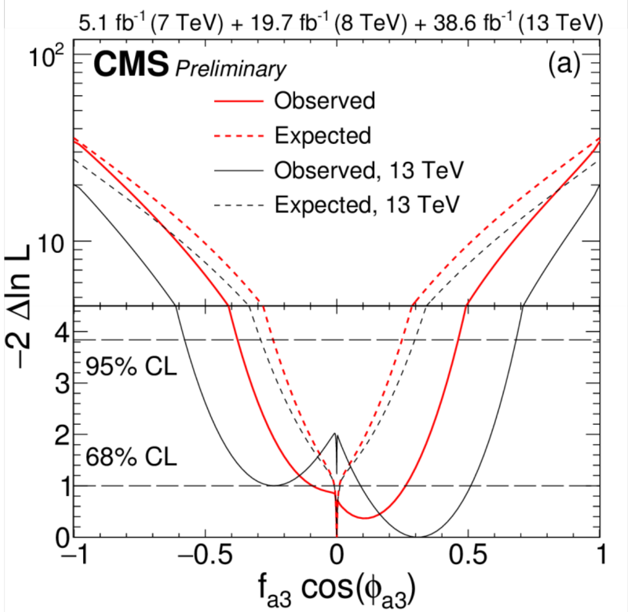




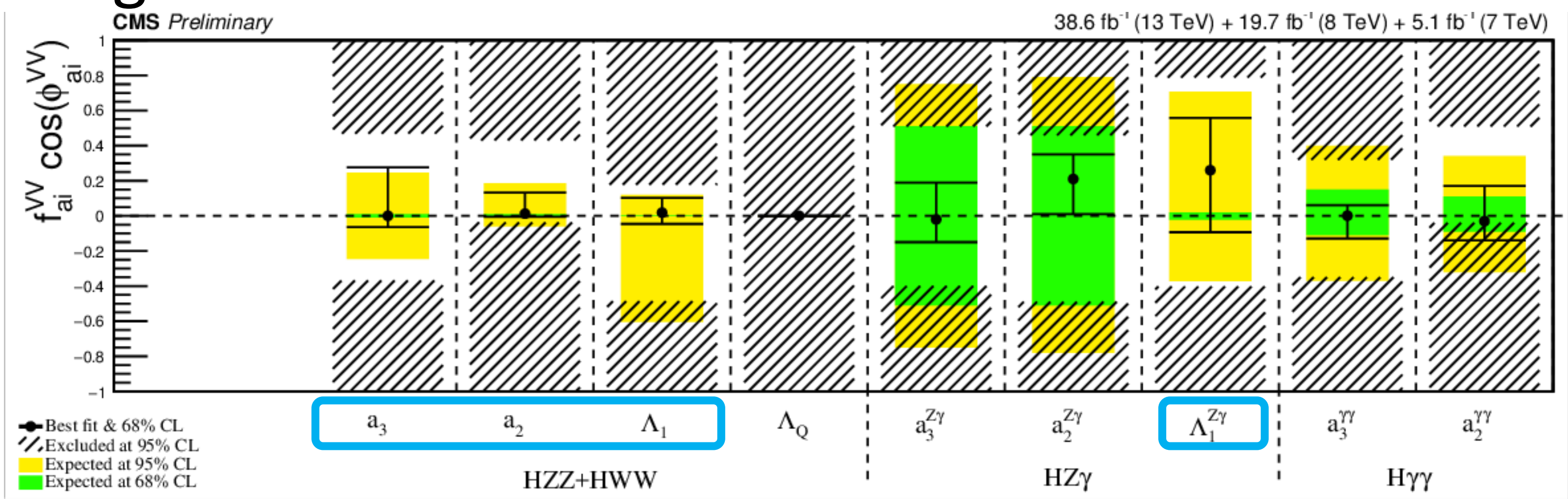


See ppt version for animations or separate indico attachment

Summary



- Constrain anomalous HVV couplings
- Decay information: 4 × more data than in Run 1
- Production information: expected 1σ exclusion of small f_{ai} values, observation falls a little short
- By the end of Run 2: expect production information to give narrow 2σ limits



Backup

Categorization

- $D_{2jet}^{VBF/ZH/WH} = \frac{p_{VBF/ZH/WH}}{p_{VBF/ZH/WH}+p_{Hjj}}$
- Separate associated production from QCD jets
- VBF-jet category:
  - exactly 4 leptons
  - 2 or 3 jets with at most one btag, or ≥ 4 jets with no btag
  - $D_{2jet}^{VBF,SM} > 0.5$ or $D_{2jet}^{VBF,BSM} > 0.5$
- VH-jet category:
  - exactly 4 leptons
  - 2 or 3 jets with at most one btag, or ≥ 4 jets with no btag
  - $D_{2jet}^{ZH,SM} > 0.5$ or $D_{2jet}^{ZH,BSM} > 0.5$ or $D_{2jet}^{WH,SM} > 0.5$ or $D_{2jet}^{WH,BSM} > 0.5$
- Untagged category:
  - Everything else

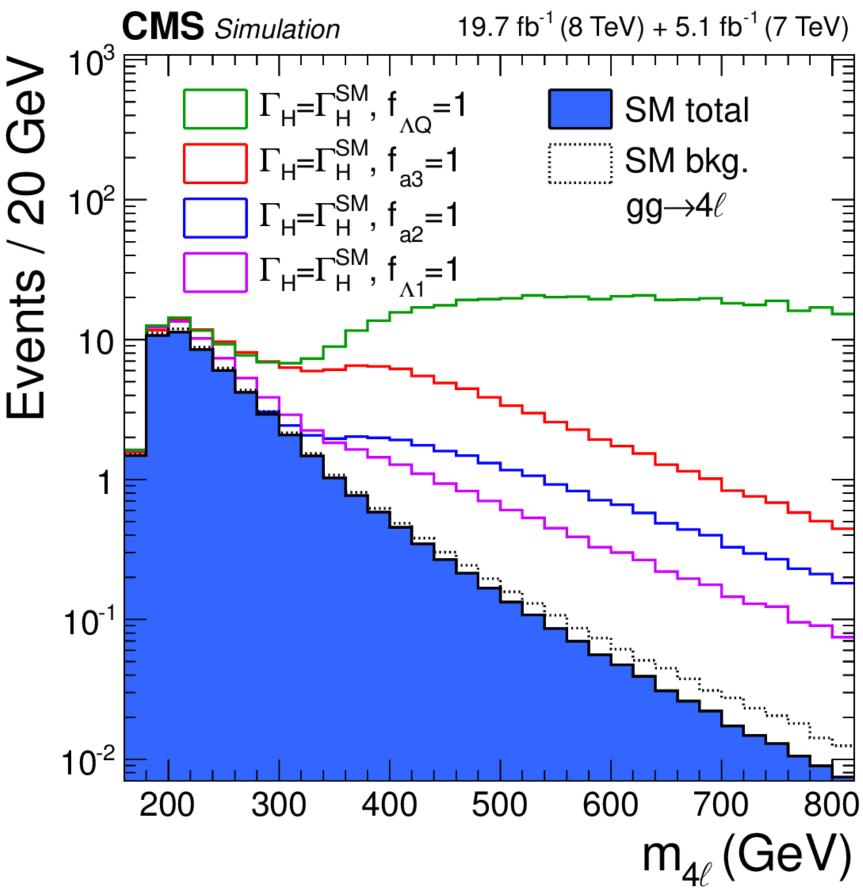
- Use D_{2jet}^{SM} and D_{2jet}^{BSM} to get optimal separation for both extreme hypotheses

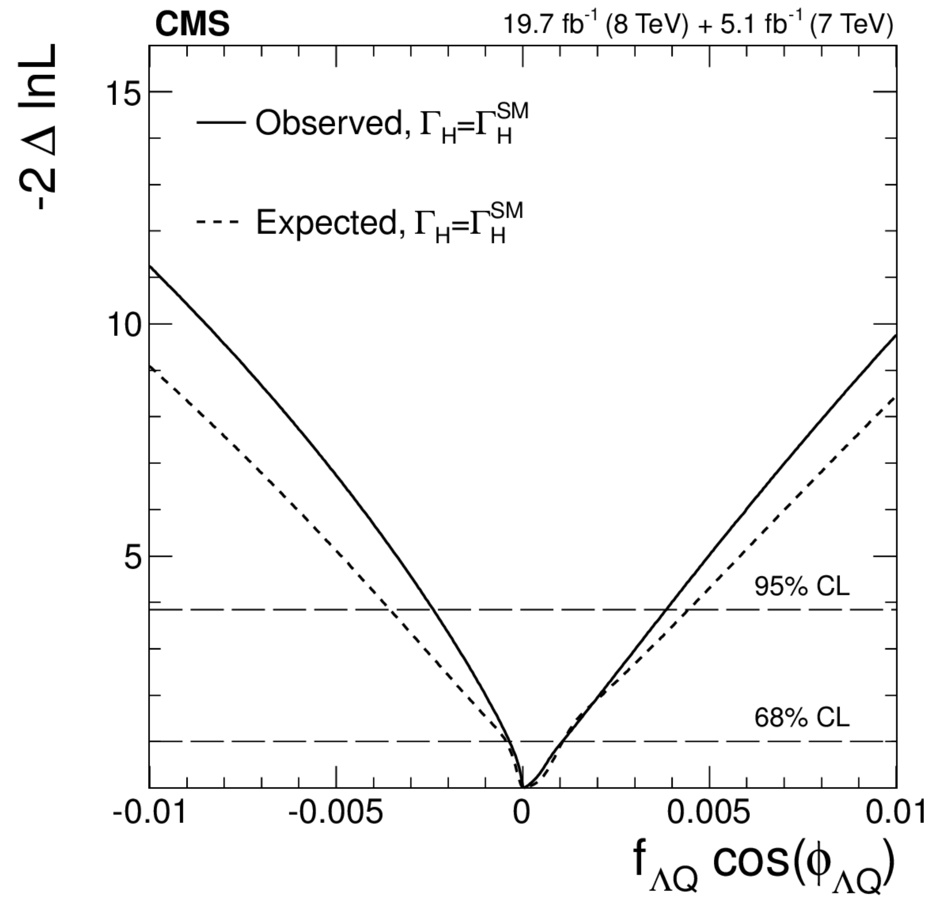
Discriminants table

category	VBF-jet	VH-jet	Untagged
target	$\mathrm{qq'VV} \to \mathrm{qq'H} \to (\mathrm{jj})(4\ell)$	$\mathrm{q\bar{q}} \to \mathrm{VH} \to (\mathrm{jj})(4\ell)$	$\mathrm{H} \to 4\ell$
selection	$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF}}$ or $\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF,BSM}} > 0.5$	$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{ZH}}$ or $\mathcal{D}_{\mathrm{2jet}}^{\mathrm{ZH,BSM}}$ or $\mathcal{D}_{\mathrm{2jet}}^{\mathrm{WH}}$ or $\mathcal{D}_{\mathrm{2jet}}^{\mathrm{WH,BSM}} > 0.5$	not VBF-jet not VH-jet
f_{a3} obs.	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0-}^{\mathrm{VBF+dec}}, \mathcal{D}_{CP}^{\mathrm{VBF}}$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0-}^{\mathrm{VH+dec}}, \mathcal{D}_{CP}^{\mathrm{VH}}$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0-}^{\mathrm{dec}}, \mathcal{D}_{CP}^{\mathrm{dec}}$
f_{a2} obs.	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0h+}^{\mathrm{VBF+dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{VBF}}$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0h+}^{\mathrm{VH+dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{VH}}$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0h+}^{\mathrm{dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{dec}}$
$f_{\Lambda 1}$ obs.	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda 1}^{\mathrm{VBF+dec}}, \mathcal{D}_{0h+}^{\mathrm{VBF+dec}}$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda 1}^{\mathrm{VH+dec}}, \mathcal{D}_{0h+}^{\mathrm{VH+dec}}$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda 1}^{\mathrm{dec}}, \mathcal{D}_{0h+}^{\mathrm{dec}}$
$f_{\Lambda 1}^{Z\gamma}$ obs.	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda 1}^{Z\gamma,\mathrm{VBF+dec}}, \mathcal{D}_{0h+}^{\mathrm{VBF+dec}}$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda 1}^{Z\gamma,\mathrm{VH+dec}}, \mathcal{D}_{0h+}^{\mathrm{VH+dec}}$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda 1}^{Z\gamma,\mathrm{dec}}, \mathcal{D}_{0h+}^{\mathrm{dec}}$

Λ_Q

CMS-HIG-14-036





- Λ_Q gives same kinematics, different mass shape
- Search from offshell region
- Limits assume $\Gamma_H = 4.1$ MeV